

ON THE
VIBRATION OF TELEPHONE DIAPHRAGMS

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THE VIBRATIONS OF TELEPHONE DIAPHRAGMS

BY CHARLES F. MEYER AND J. B. WHITEHEAD

HISTORY

Investigations of the vibrations of telephone diaphragms have been published by Rayleigh,¹ Wien,² Kempf-Hartmann,³ Taylor⁴, Gati⁵ and others. Rayleigh and Wien measured the value of the simple harmonic current which would just produce an audible tone in the receiver at different frequencies. They found that at certain frequencies the current required was a minimum, and Wien concluded that these minima showed the existence of natural vibrations of the diaphragm, but realized that the variation in sensibility of the ear with pitch played possibly a larger part in the difference of current required at different frequencies than the natural vibrations themselves.

Kempf-Hartmann fastened a mirror on the diaphragm of a receiver and photographed on a moving film the oscillations of a spot of light reflected from the mirror. By passing direct current interrupted about 100 times per second through the telephone he was able to photograph the natural oscillations of the diaphragm which were produced at each make and break, and showed also that when the diaphragm had been given an impulse its reaction could be detected after about $1/2000$ of a second.

Taylor has plotted curves showing the connection between the least current producing an audible tone and the frequency, his work being similar to that of Rayleigh and Wien. He noticed

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1. Rayleigh. "Theory of Sound," I, p. 473.
 2. Wien. *Annalen d. Phys.*, IV, p. 450, 1901.
 3. Kempf-Hartmann. *Annalen d. Phys.*, VIII, p. 481, 1902.
 4. Taylor. PROCEEDINGS A. I. E. E., XXVIII, 1184, 1909.
 5. Gati. *Electrician*, LXVI, p. 456, 1910.

that as the alternating current generator from which he obtained his current accelerated or slowed down there were certain frequencies at which the sound from the receiver was very much increased, and he plotted rough curves showing this.

Gati has worked with transmitters. He produced before the diaphragm a sound of which the frequency was varied, but the amplitude was kept as constant as possible. The transmitter was in circuit with a battery and the primary of a transforming coil. To the secondary of the coil he connected the capacity required to produce electric resonance at each frequency and measured the current in the secondary circuit. Plotting curves between frequency and current a decided maximum is obtained showing resonance at about 700 vibrations per second.

The mathematical theory of the free oscillations of circular membranes and plates has been developed. It shows that the nodes are either circles about the centre, or diameters symmetrically distributed⁶, this holding true for plates with either a free or a clamped boundary; the boundary of membranes is, of course, necessarily fixed. Rayleigh gives the following formula for the frequency of the lowest natural vibration of a clamped plate.

$$n = \frac{3 \cdot 2^2 \sqrt{q h}}{2 \pi a^2 \sqrt{3 \rho (1 - \mu^2)}}$$

where q = Young's modulus.

μ = Poisson's ratio.

ρ = volume density.

$2h$ = thickness of plate

a = radius of plate.

He applies the formula to the case of a receiver diaphragm which he measured and found 991 as the fundamental frequency. No experimental verification of this seems to have been attempted.

OBJECT

The present work was undertaken to obtain further and more accurate information concerning the way in which the diaphragms in the transmitter and receiver vibrate when acted on by periodic forces of simple wave form of different frequencies. Also to obtain quantitative data on the influence of the free periods, and to determine to what degree of approximation the

6. Rayleigh. "Theory of Sound," Vol. I, pp. 331, 366.

form of the vibration of the diaphragm follows that of the impressed force. The question of the localization of the nodes and loops at the higher resonance frequencies is also interesting, but it has thus far evaded solution.

WORK ON THE RECEIVER

Arrangements and Apparatus. The receiver is simpler in construction than the transmitter and is therefore more easily investigated. With the receiver the problem is to pass through it an alternating current of simple wave form, as nearly simple harmonic as obtainable, and to record the form of the current, and the corresponding oscillation of the diaphragm. The amplitude of the oscillation of the diaphragm for the same current at different frequencies, plotted against frequency would then give the resonance curve for the diaphragm. For producing the alternating currents two special generators with smooth body armatures were used for low frequencies. For the principal range a third generator was used. With these three machines frequencies from $16\sim$ to $3000\sim$ could be attained. The current wave form was recorded by a Duddell double high frequency oscillograph, used simultaneously as oscillograph and ammeter. An oscillograph of this type has a free period of from 8000 to 10,000. It may hardly be relied upon to record with any accuracy a wave of over three or four hundred cycles. In the present case, however, the current wave is, with a few exceptions, very nearly pure, and the question of wave form does not enter markedly into the results of the work.

The method adopted for recording the oscillations of the diaphragm was as follows: A small fragment of mirror was mounted directly on the diaphragm by means of wax or cement, and its vibrations recorded by a spot of light reflected upon a photographic plate. It is easy to mount the mirror rigidly, and its mass which may be 0.007 of a gram or under, is too small to influence the motion of the diaphragm greatly. There can further be no doubt that the angular deviation of the mirror is the angular deviation of the diaphragm, at the point where it is mounted.

DIAPHRAGM A

The first receiver worked with was one of the ordinary bipolar type. Its characteristics were: Total diameter of diaphragm 5.42 cm. (2.14 in.). Inside diameter of clamping ring in cap 4.98 cm. (1.96 in.), this being the effective diameter of the dia-

phragm. Thickness of diaphragm with enamel on front face 0.03 cm. (0.012 in.). Thickness bare at edge 0.023 cm. (0.009 in.). Distance between pole pieces and plane of clamping ring of diaphragm 0.05 cm. (0.02 in.). The air gap between pole pieces and diaphragm is less than this as the diaphragm is permanently bent inwards by the attraction of the magnet. The part of the cap extending over the diaphragm was cut out in order to make room for the small mirror which was fastened on. See Fig. 1. The mirror was placed about half way between the center and edge. The diaphragm was so oriented over the pole pieces that the mirror came on the perpendicular bisector as shown in Fig. 2. The receiver was then set up so that the mirror came on a horizontal diameter. Pulling in of the diaphragm corresponded to a motion to the right of the light spot on the photographic plate.

Some of the photographs obtained for this diaphragm are



FIG. 1.—CAP OF RECEIVER—THE SHADED PORTION WAS CUT AWAY.

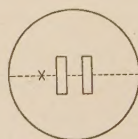


FIG. 2.—THE X MARKS THE POSITION OF THE MIRROR ON THE DIAPHRAGM

shown in Figs. 3 and 4, with frequencies noted for each set. The curves on the left are the oscillograph records of the current through the receiver, the number at the side giving its value in milliamperes (effective), calculated from a knowledge of the sensibility of the oscillograph. The curves on the right are the traces from the diaphragm, the accompanying figures giving the value of the angular deflection in radians $\times 10^{-4}$, calculated from the dimensions of the optical system. As these latter curves are unsymmetrical it is impossible to speak of their amplitudes, so the total deflection from one extremity of swing to the other is given; this quantity will henceforth be referred to as the "range" of the oscillation. The numbers on the extreme right-hand side of the figure give the frequencies of the vibration in cycles per second. In all of the photographs time proceeds upwards, as shown by the arrow. In the first traces a break is noticeable about the middle of the vibration, which indicates the rest positions of the spots of light. This break was produced by

CURRENT

DIAPHRAGM

38.4 MILLI-
AMPERES

RADIANS

15.8×10^{-4}

60 ~

32.6 "

13.6 "

18.4 "

6.7 "

232 ~

68.0 "

21.8 "

32.1 "

9.8 "

332 ~

18.8 "

5.5 "

32.5 "

12.2 "

21.4

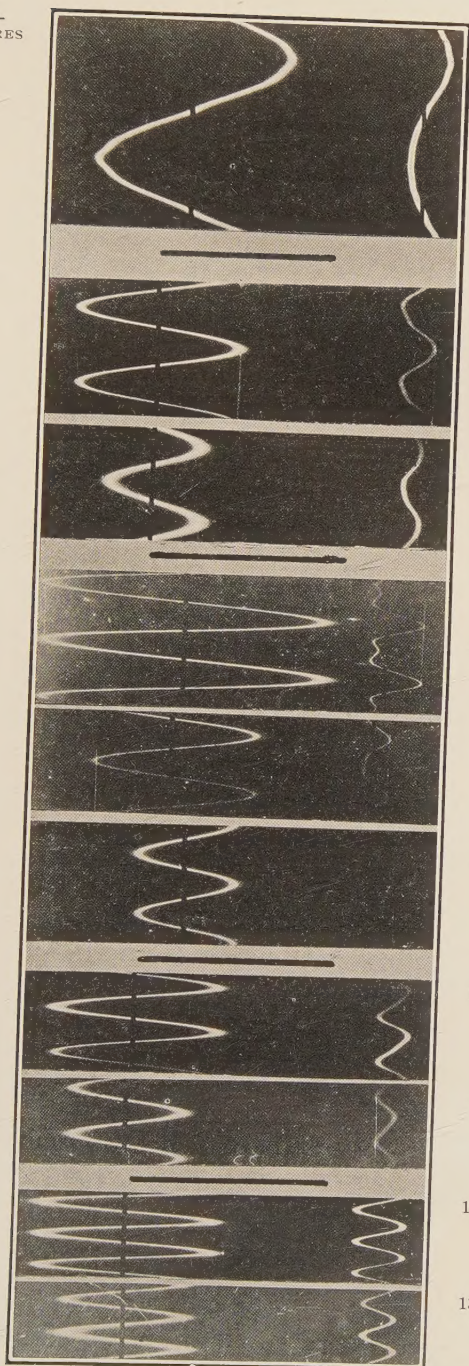
7.9 " 403 ~

35.1 "

19.6 "

23.6 "

13.3 " 540 ~



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FIG. 3—RECEIVER DIAPHRAGM A



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CURRENT

DIAPHRAGM

36.7 MILLI-
AMPERES

RADIANS

26.5×10^{-4}

610 ~

20.3 "

13.3 "

20.8 "

24.0 "

680 ~

53.3 "

20.1 "

1066 ~

19.5

7.2 "

61.1 "

9.8 "

1292 ~

37.8 "

5.7 "

46. "

1814 ~

41.7 "

9.3 "

2600 ~

31.6

7.6 "

51.6 "

3.1 "

2700 ~

37.5 "

2.2 "

54.2 "

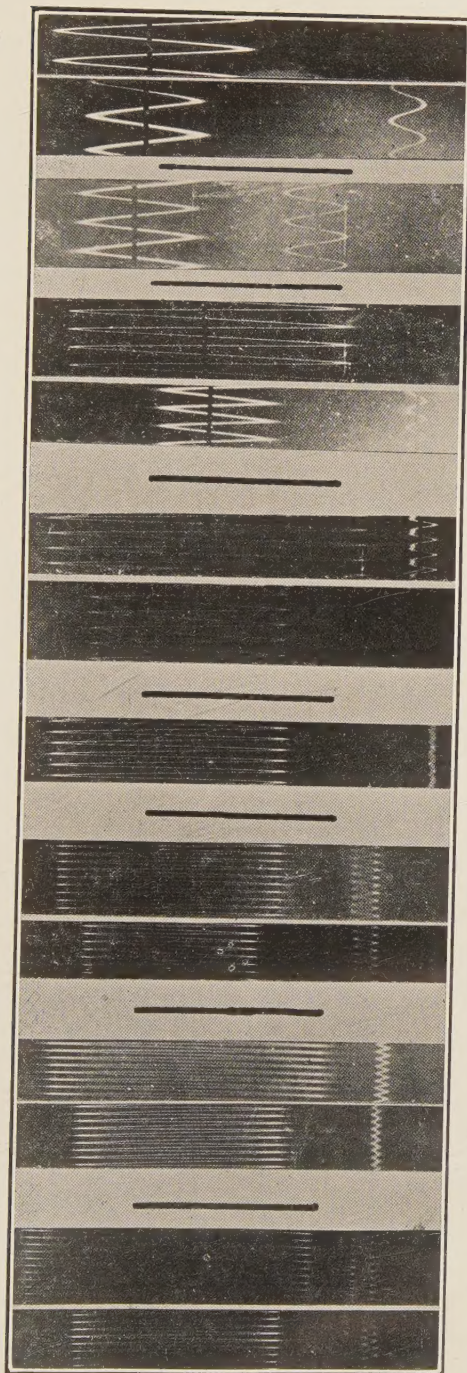
8.6 "

2794 ~

38.8 "

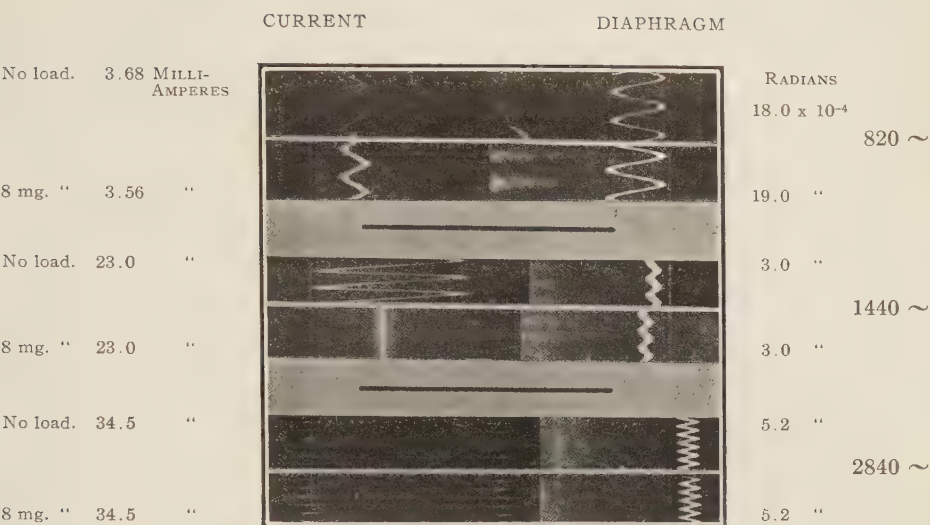
4.8 "

Time



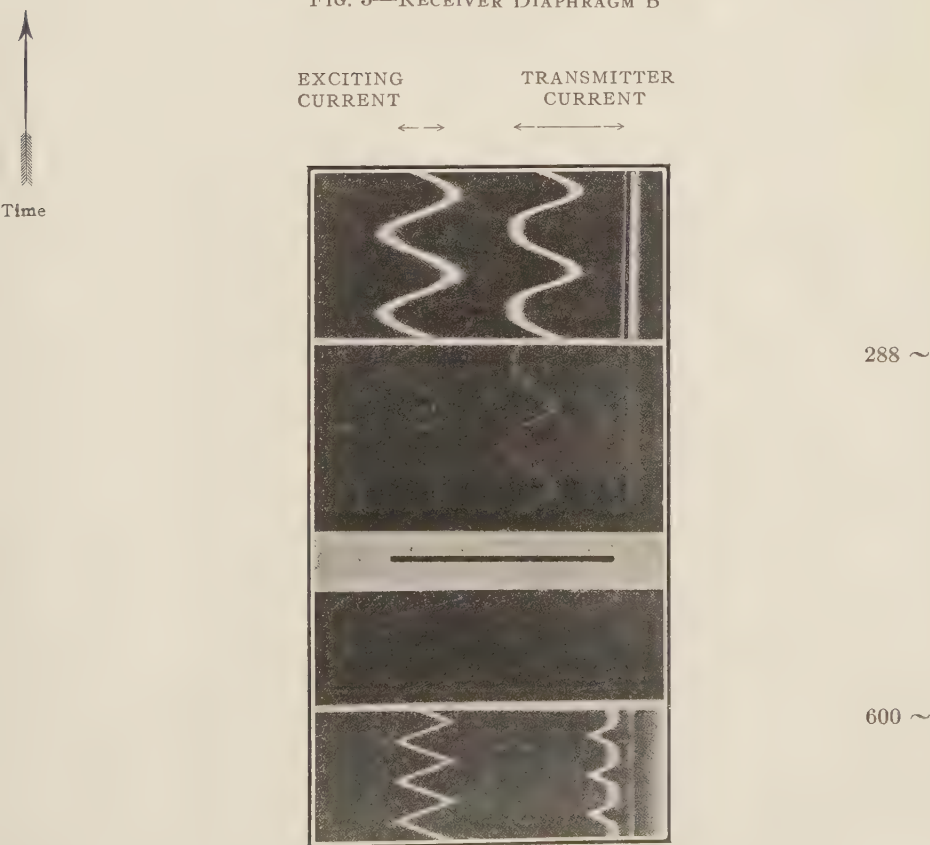
[MEYER AND WHITEHEAD]

FIG. 4—RECEIVER DIAPHRAGM A



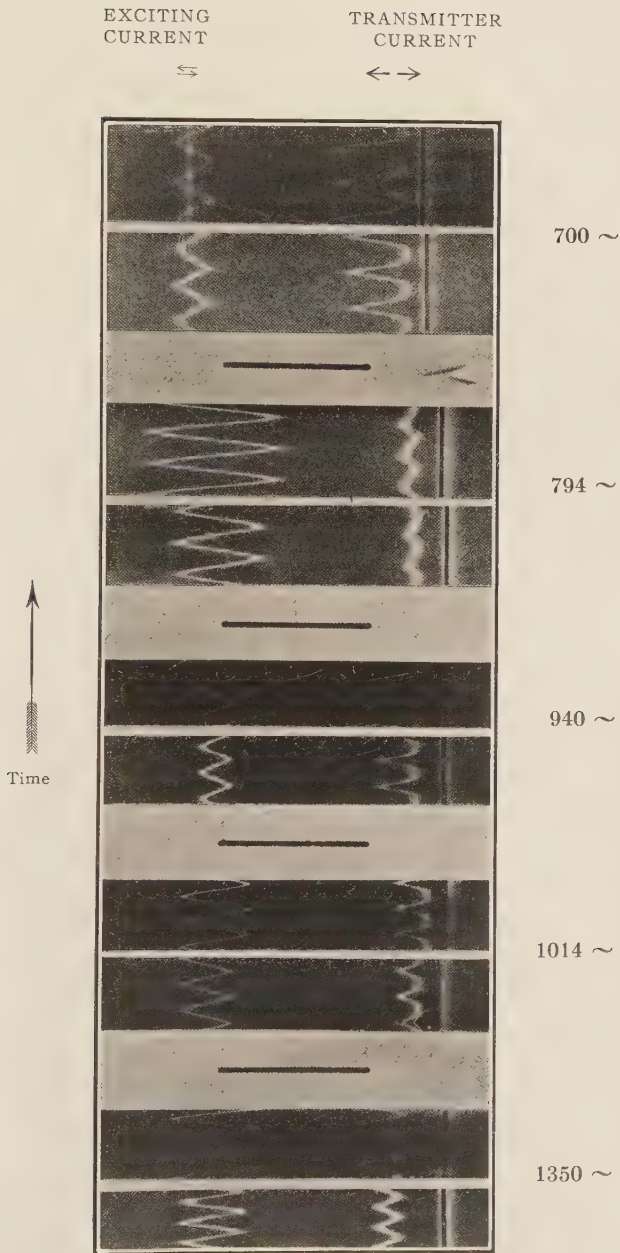
[MEYER AND WHITEHEAD]

FIG. 5—RECEIVER DIAPHRAGM B



[MEYER AND WHITEHEAD]

FIG. 6—TRANSMITTER



[MEYER AND WHITEHEAD]

FIG. 7—TRANSMITTER

placing a fine wire in the path of the beam of light when there was no current, but the wire was soon abolished as it introduced unnecessary complications.

The diaphragm trace for 60 cycles is seen to be somewhat unsymmetrical the curve being pointed on the right, that is when the diaphragm is nearest the pole pieces. At 232 cycles for a range of 13.6 the curve is rather unsymmetrical, but for a range of 6.7 the irregularity is less marked. At 332~, and 1292~ also, the irregularities are seen to be greater for greater ranges while for most of the other curves this is not noticeable. The development of the dimple in the curve for 332 and 1292 ~ at the point where the diaphragm is furthest from the poles is rather surprising; it will be seen later that 332 ~ shows a peculiarity in another respect. It might be expected from the following considerations to find greater regularity in the photographs for small ranges.

The force on the diaphragm is proportional to the square of the induction. If we consider the induction B as made up of a constant part B_0 due to the permanent magnetism, and a variable part B_1 , due to the current, we have for the original force

$$F_0 = c B_0^2$$

and for the variable force

$$F = c B^2 = c [B_0^2 + 2B_0 B_1 + B_1^2] \quad (2)$$

The increment of the variable force over the original force determines the motion of the diaphragm. Its value is

$$\Delta F = F - F_0 = c [2B_0 B_1 + B_1^2]$$

If B_1 is sufficiently small we may neglect its square and write

$$\Delta F = 2c B_0 B_1 \quad (3)$$

So that, if B_1 is made to vary harmonically, ΔF will do so. In the present work the currents have been kept nearly harmonic in all cases. The variation in the air gap between the pole pieces and the diaphragm, would prevent B_1 from being strictly proportional to the current, but for sufficiently small vibrations the influence of the variation in the air gap may be neglected.

The ranges of all the traces were carefully measured. The results obtained for the first diaphragm are plotted in the curves

of Figs. 8, 9, and 10. The abscissæ are current through the receiver, expressed in milliamperes (effective). The ordinates are the angular range of oscillation of the diaphragm, expressed in radians $\times 10^{-4}$. Each curve gives the relation between current through the receiver and oscillation of the diaphragm at a given frequency which is marked beside it. The curves are all plotted to the same scale and put in separate figures to avoid crowding. They show that an approximately linear relation

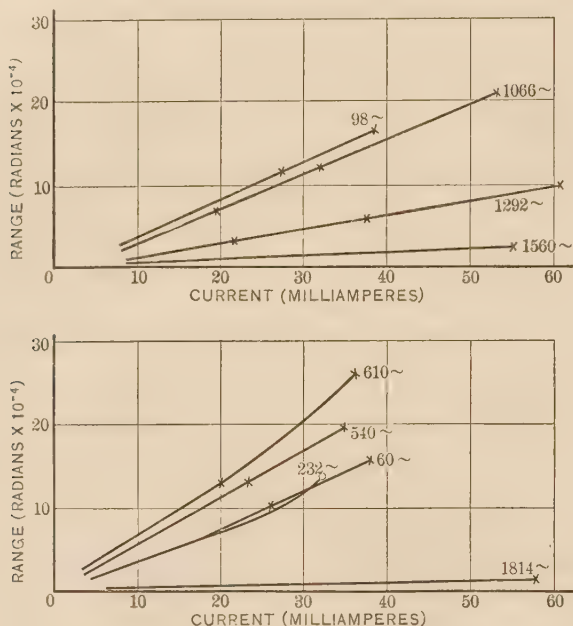


FIG. 8.—RELATION BETWEEN CURRENT THROUGH THE RECEIVER, AND RANGE OF OSCILLATIONS OF THE DIAPHRAGM AT DIFFERENT FREQUENCIES.

exists between the current and deflection of the diaphragm, even to the large values of current here used. The sound of the telephone for the greater currents was sufficient to be heard all over the room.

From each of the curves of Figs. 8, 9, and 10, the angular oscillation corresponding to a current of twenty milliamperes, at the frequency for which the curve is taken, can be read off. In Fig. 11 a curve is plotted between the frequency as abscissa, and the angular oscillation as ordinate, showing the effect of

change of frequency on the angle of oscillation, this being the so-called resonance curve for the diaphragm. It will be noticed that the curve starts out horizontally, then drops to a minimum at 300 ~ from which it rises and reaches a maximum at 720 ~, at which the range of oscillations is about five times that of the minimum, and about four times that at the lowest frequency. After 720 ~ there is no other maximum until 2600 ~, and then shortly after this there appears to be another, but this was not

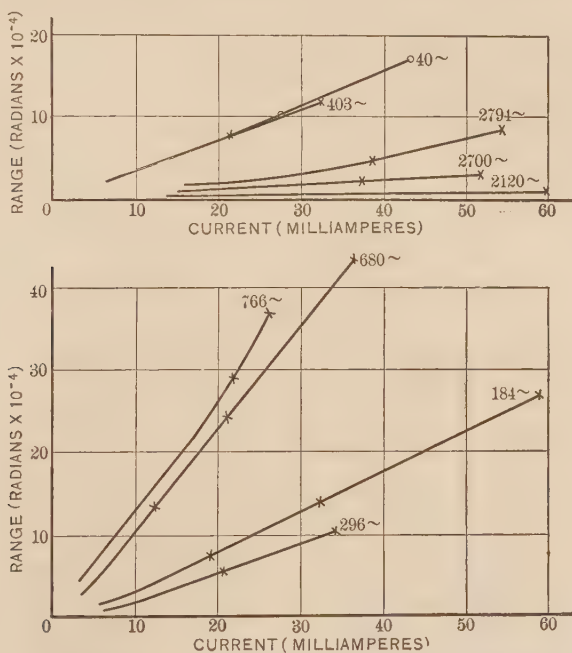


FIG. 9.—RELATION BETWEEN CURRENT THROUGH THE RECEIVER, AND RANGE OF OSCILLATION OF THE DIAPHRAGM AT DIFFERENT FREQUENCIES.

quite reached as it was not desired to overspeed the machine at the time these records were obtained. It is rather surprising to find the minimum at 300, before the first maximum. At first its real existence was doubted but the appearance of a similar dip in the curve for the next diaphragm, with an entirely different make of receiver, seems to indicate a real effect. It should be remembered that the damping of the diaphragm in a receiver is not purely mechanical, but is partly electromagnetic and this may have a bearing here. The mechanical effect can be expressed

by a term of the usual form $k \frac{dx}{dt}$ in the differential equation of motion of the diaphragm. The electromagnetic damping we may consider to be made up of two parts. One of these is due to eddy currents set up by the motion of the diaphragm in the permanent magnetic field. It would be present if the diaphragm were executing free vibrations. This also could be expressed by a term of the form $k \frac{dx}{dt}$. The other part is due to hysteresis

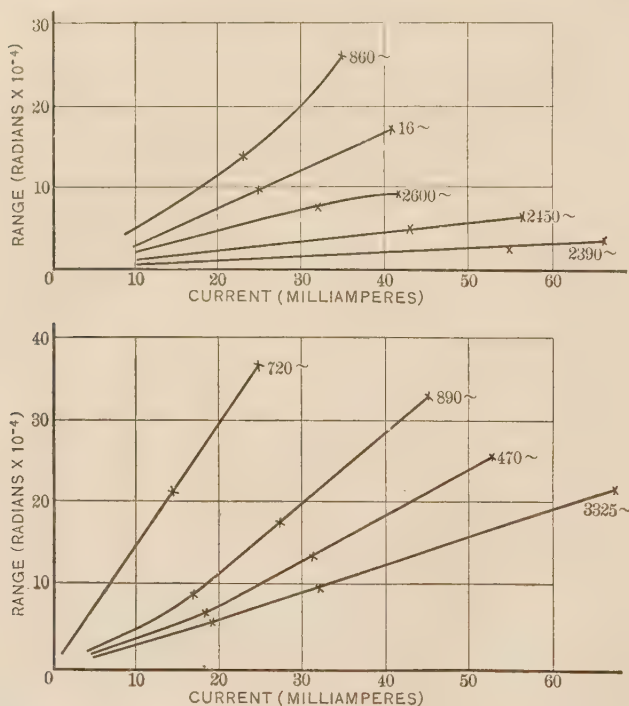


FIG. 10.—RELATION BETWEEN CURRENT THROUGH THE RECEIVER, AND RANGE OF OSCILLATION OF THE DIAPHRAGM AT DIFFERENT FREQUENCIES

and eddy currents caused by the current in the receiver. This would increase with the frequency so that we are dealing here not with a constant damping coefficient, as is usually supposed in the treatment of forced oscillations, but with one that increases with frequency. The minimum in the resonance curve appears at about 300 ~ and it is the trace at 332 ~ to which attention was called above, which shows the dimple. The plate

for 296 $\sim$ (not reproduced) was exposed in two sections giving traces very similar to the lower two of 332 $\sim$. This plate was obtained before the one for 332 $\sim$ and the range was not carried high enough to get the dimple. It cannot be definitely said that the minimum of the curve and the dimple in the trace are causally connected, but the coincidence is rather striking.

The resonance curve Fig. 11 covers the range of the important frequencies existing in the human voice. The lowest tone reached by man in singing is about 65 vibrations per second. The highest reached by a woman is 1036, but this tone contains harmonics of higher frequencies. A number of investigations have been per-

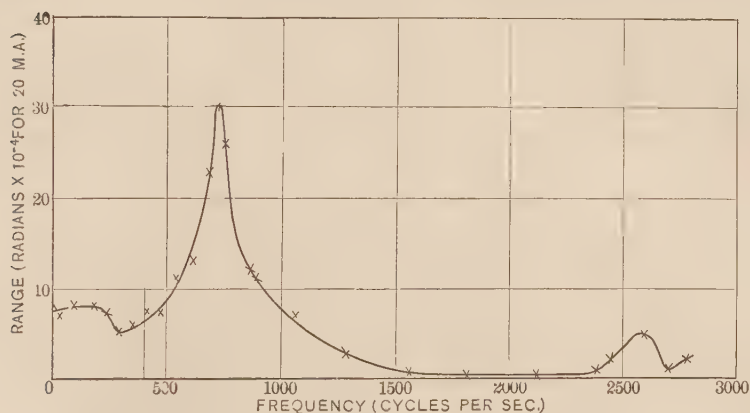


FIG. 11.—RESONANCE CURVE FOR DIAPHRAGM A. GIVING THE RELATION BETWEEN FREQUENCY AND RANGE OF OSCILLATION FOR A CONSTANT CURRENT.

formed on the vibrations contained in vowel sounds. According to results obtained by Bevier⁷ the prominent frequencies are:

For <i>a</i> as in <i>hat</i>	650	1050	1550
" <i>e</i> " " <i>pet</i>	620	1050	1800
" <i>i</i> " " <i>pit</i>	575	1850	
" <i>i</i> " " <i>pique</i>			2050

In the consonants, especially those of the hissing type, very much higher frequencies exist, going in some cases as high as 10,000. These consonants have not the importance in speech that the vowels have, and it may well be said that the prominent

7. *Phys. Rev.*, 1901, 1902, 1903. Quoted by Barton "Text-Book of Sound," p. 672.

vibrations are included between 300 and 3000, probably not many lying above 2000.

We may obtain a comparison between the fundamental frequency of the diaphragm determined experimentally, with that to be expected from Rayleigh's formula. The greatest ordinate of the resonance curve comes at 720. This ordinate for any system lies at a somewhat less frequency than its free vibrations. Further the actual frequency is somewhat less than it would be if there were no damping. It is this last value which is given by Rayleigh's formula. By applying the theory of a system with one degree of freedom to the resonance curve of Fig. 11, a simple calculation shows that if there were no damping the free frequency of diaphragm "A" would be 732. This is 12 vibrations a second higher than the point for the maximum ordinate of the curve. The difference is not greater than the error in measuring the frequency. Let us now substitute in equation (1). We may take

$$g = 2.0 \times 10^{12}$$

$$\mu = \frac{1}{4}$$

$$\rho = 7.7$$

which gives

$$n = 2.41 \times 10^5 \times \frac{2h}{a^2};$$

from the measurements of the present diaphragm,

$$2h = 0.023 \text{ cm.}$$

$$a = 2.5 \quad "$$

hence

$$n = 890$$

this being the value required by Rayleigh's formula, whereas the value obtained experimentally is 732. The agreement is not very good but a better result is hardly to be expected. The diaphragm has 0.007 cm. (0.003 in.) of enamel on its front face, which probably loads it down without adding much to its stiffness, thus causing the actual value of the free frequency to be lower than the calculated one. The measurement of the thickness of the diaphragm is not very accurate, only a small spot on the edge being available for this, and moreover the value of Young's modulus substituted in the equation may not be the correct one for the iron of the diaphragm. It cannot be told in

what direction more accurate values for these last two quantities would change the result.

DIAPHRAGM B

Another receiver designated as No. 122 *W*, also of the bipolar type, was next investigated. Its characteristics were: Total diameter of diaphragm 5.51 cm. (2.17 in.). Inside diameter of clamping ring 5 cm. (1.97 in.). Thickness of diaphragm over enamel and varnish 0.028 cm. (0.011 in.). Thickness bare at edge 0.023 cm. (0.009 in.). Distance between pole pieces and plane of clamping ring of diaphragm about 0.03 cm. (0.012 in.).

It seemed desirable to ascertain whether the mirror had any noticeable effect on the form or range of the oscillation, so in this set of exposures the current was kept as nearly constant as possible for each plate. One section was exposed with a load of 8 mg. wax placed on the diaphragm as near to the mirror as possible, and the other section was exposed without the load. Some of the photographs are reproduced in Fig. 5. In none of these is there any noticeable difference in wave form when the load is on and off, nor is any difference shown in the other photographs which are not reproduced. The traces were all carefully measured. The differences in width are of the order of the errors of measurement, which range from, say, 5 per cent when the traces are as wide as those for 820 $\sim$ to 15 or 20 per cent for narrow traces, as for 1440 $\sim$. The measurements on the same trace usually check up to one or two per cent if the range of the trace is a centimeter or more, but in measuring traces of different photographic intensity the accuracy is probably not so great. The figures for 820 $\sim$ show an increase of 8 per cent for the loaded case over that for no load; this may be a real effect.

Fig. 12 gives the resonance curve as nearly as it can be plotted from the scant data obtained for this diaphragm. Frequency is plotted as abscissa, and the ratio of diaphragm oscillation to current as ordinate. If we assume the linear relation of current and diaphragm oscillation for a fixed frequency this gives the same curve as Fig. 11 to within a constant factor. We see that the minimum before the first maximum is again present, and in a more marked degree than for the first diaphragm. The maximum ordinate is about five times that at the minimum as before, but only three times that at the lowest frequency. However it is not entirely certain that the maximum comes at 820 $\sim$ as drawn. When watching the light spots this appeared to the

eye to be about the maximum and so the photograph was made at this frequency. If more points had been obtained they might have shown that the maximum really lies at a somewhat different frequency, and has a 10 or 20 per cent greater value. The curve shows no further resonance points up to the highest speed the machine attained, but they doubtlessly would have been found if it had been possible to go high enough. This diaphragm had approximately the same characteristics as the first so if we apply Rayleigh's formula we again get 890 as the natural frequency, the agreement with the experimental value being somewhat better this time.

GENERAL OBSERVATIONS

More diaphragms, and diaphragms of different characteristics might have been examined by the method here used, but it was

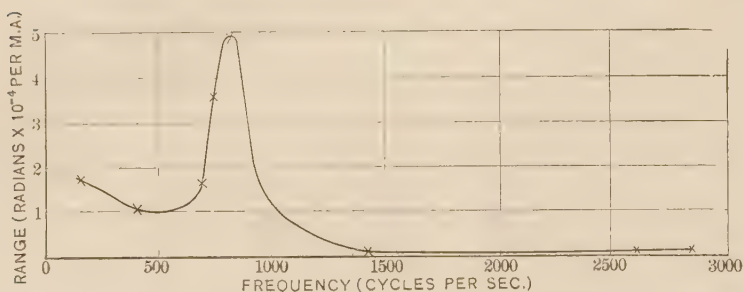


FIG. 12.—RESONANCE CURVE FOR DIAPHRAGM B.

thought that before the investigation was extended in this direction further knowledge should be obtained about the motion of some one diaphragm. It was pointed out above that when a circular plate is vibrating freely, the nodes are circles and diameters.⁸ In the case of a clamped diaphragm this means that the nodes may be located as shown in Fig. 13. These drawings are for the five lowest modes of vibration and are given in the order of ascending frequency. We may expect that in the case of a telephone diaphragm some of these types of vibration will be present. It cannot be said in advance which ones will occur nor to what extent they will do so. This depends on the frequency of the impressed force and on the way in which it is applied, and can only be found by experiment. Hence we may suppose that

8. Winkelmann's "Handbuch der Physik, II," p. 372, ed. 1909. Rayleigh. "Sound," Vol. I, pp. 331 and 366.

by fixing a mirror in one spot (*e.g.*, over the perpendicular bisector of the pole pieces), we cannot learn all that should be known about the motion of the diaphragm, and this is borne out, even to a more marked degree than was expected, by visual observation of the spot of light at certain frequencies. The spot ordinarily vibrated in a horizontal direction. This is what would be expected if the vibration consisted of a motion of the diaphragm as a whole (Fig. 13*a*,) or if there existed an internal circular node (Fig. 13*d*,). We may refer to this as a "circular" vibration. At certain frequencies the spot of light vibrated, not horizontally, but obliquely. An oblique motion would be produced

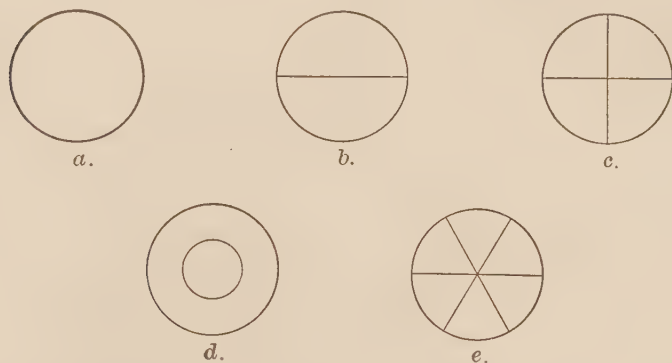


FIG. 13.—REPRESENTING THE FIVE LOWEST MODES OF FREE VIBRATION OF A CIRCULAR DIAPHRAGM.

- a*.—The boundary as the only node—diaphragm vibrating as a whole.
- b*.—One diameter as node—the two halves of the diaphragm vibrating in opposite phase.
- c*.—Two diameters as nodes—adjacent quadrants are in opposite phase.
- d*.—Two circles as nodes—the inner and outer areas are in opposite phase.
- e*.—Three diameters as nodes—adjacent sectors are in opposite phase.

if there were superimposed on the circular vibration a vibration having one or more diameters as nodes, as in Fig. 13 *b c*, or *e*. We may speak of this motion as a "diametral" one. The mirror need not be located on a node to show this component, but would do so to some extent if it were located anywhere except on a loop. This component cannot be symmetrical about the center of the diaphragm.

It is not at once evident why the diametral vibration should be introduced at all. If we assume the complete symmetry of the diaphragm about its center, and of the pole pieces about the diameter bisecting them perpendicularly, there is no reason to

expect it. We must look for a lack of symmetry somewhere. The mirror on the diaphragm suggests itself, but the weight of the mirror was only 4 mg. and it seems improbable that so small a load could be responsible for the vibration. It was thought that some sort of asymmetry must exist in the poles, and if this were the case then a rotation of these behind the diaphragm ought to make the nodal diameter rotate in the diaphragm, keeping a fixed position with reference to the poles. This would allow an exploration of the motion, so to speak, around the diaphragm without moving the mirror or the diaphragm itself. A receiver (122 W) exactly like the one used with diaphragm "B" was fitted up to allow the rotation of the poles. With this instrument it was found that the diametral component recorded by the spot of light changed markedly as the pole pieces were rotated; it passed from zero through a maximum and back to zero in about half a revolution. But it was also noticed that there was a decided change in the intensity of the sound as the rotation took place, which, of course, should not exist if the diaphragm were symmetrical and the nodal diameter were merely being turned therein. Moreover the maximum diametral components recorded by the image coincided with the maximum sound, so that possibly the main thing shown was that the amplitude of the diametral vibration of the whole diaphragm depended on the orientation of the diaphragm over the poles. Three things presented themselves in explanation of this fact: First, mechanical imperfections in the rotating part might cause the poles to approach the diaphragm in certain positions and recede at others. Second, the influence of the weight of the mirror might make one direction in the diaphragm different from another. Third, the grain of the diaphragm may be the cause. This was suggested by Kempf-Hartmann⁹ as a possible cause of asymmetry. Some rough experiments were at once instituted to decide between these three possibilities, and it is certain that mechanical imperfections play only a small part if any at all. No decision could be made between the influence of the mirror and grain, but it is thought that this can be done in the future. If it develops that the orientation of the grain in the diaphragm over the poles plays an important part in determining to what extent the diametral vibrations are introduced, it would appear to be a matter of some importance.

Whether these vibrations are a help or a hindrance in the

9. Kempf-Hartmann. *Annalen*, VIII, p. 492, 1902.

transmission of speech it is difficult to say. It is generally considered that the fundamental tone of the diaphragm falls within the range of the principal frequencies of the voice, and this is borne out by comparison of the curves of Figs. 11 and 12 with the data given on the frequencies for different sounds. The amplitude of the circular vibration is small between the fundamental and the next higher resonance tone. Sounds of certain pitch are therefore very much magnified in relation to others. The frequencies of the vibrations with one diameter and two diameters as nodes lie below the frequency for the second circular vibration. From the observations discussed above it appears that a telephone diaphragm may be made to take up these nodes of vibration by properly orienting it over the pole pieces or by properly loading it. Now, might it not be possible by deliberately introducing the diametral vibrations, both in transmitter and receiver, and choosing the sizes of the diaphragm in such a manner that the maxima of the resonance for the one diaphragm, coincide with the minima of the resonance for the other, to maintain more nearly the relation between the amplitudes of sounds of different frequencies?

WORK ON THE TRANSMITTER

Arrangements and Apparatus. For the transmitter the general problem is similar to that for the receiver, namely, to exert an oscillating force of known form on the diaphragm and record the vibration produced by it. As in actual use the transmitter is acted on by sound waves, the most natural thing would be to use these for the impressed force, but experimental difficulties arise which make this impracticable. It is difficult, if not impossible, to get a source of sound which is sufficiently loud, and at the same time gives a pure tone of which the pitch and intensity may be easily varied and measured over a wide range. Moreover when working with sound sources in an enclosed space, such as the room of a laboratory, there are always standing waves set up between the walls of the enclosure which would introduce a further uncertainty in determining the intensity of the sound which is incident upon the transmitter diaphragm. For these reasons no attempt was made to use a sound source. From the work on the receiver the conclusion seemed justified that the pull produced on the diaphragm by the receiver magnet is nearly harmonic for a harmonic current, and the amplitudes of the force and current are proportional if the

current is not too great. It was accordingly decided to use a receiver magnet for producing the force acting on the transmitter diaphragm, as this allows the frequency and amplitude to be easily varied and measured. The magnet of a receiver was mounted rigidly in front of the transmitter. A small iron disk was shellaced on to the diaphragm to have some magnetic material for the magnet to act on, as the transmitter diaphragm themselves are of aluminum. The necessity of using the disk and the fact that the magnet produces a central force instead of a distributed one, as does a sound wave, are disadvantages of this method. (The weight of the disk was 0.81 gram.)

The current from the alternating current generator was passed through the coil of the receiver magnet, and the current wave recorded on the oscillograph.

For recording the vibration of the diaphragm the mirror method would have had certain advantages, but with a system as stiff as the transmitter the amplitude would not be great enough. Current from a storage battery was passed through the transmitter and the second vibrator of the oscillograph in series, and the variation of current in the transmitter due to the vibration of the dia-

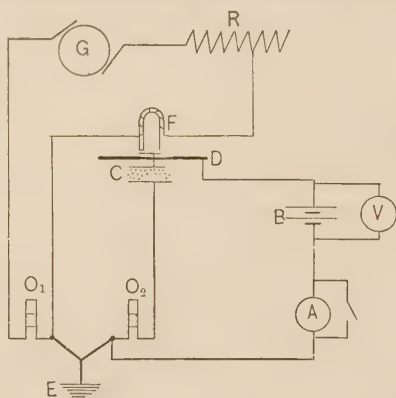


FIG. 14.—ELECTRICAL CONNECTIONS IN WORKING WITH THE TRANSMITTER.

phragm was recorded on the same photographic plate on which the curve of the current through the magnet was recorded; the variation of current in the transmitter was taken as a measure of the oscillation of the diaphragm. The electrical connections are shown in Fig. 14. In one electrical circuit which will hereafter be referred to as the "magnet circuit," the high frequency generator G , the oscillograph O_1 , the coil on the magnet F and the resistance R are in series. In the other circuit which will be called the "transmitter circuit," the current flows from the storage battery B to the diaphragm D through the carbon granules box of the transmitter C to the oscillograph O_2 , and through the milliammeter A back to the battery. The battery consisted of three storage cells; the voltage remained constant at 2.9 volts throughout. The two circuits

had the point *E* in common at which they were connected to earth. The action of the apparatus is simple. The alternating current in the coil of the magnet *F* causes the diaphragm *D* to vibrate. Before the beginning of the vibration the current in the transmitter is steady and can be read on the milliammeter *A*. This steady current causes a steady deflection of the oscillograph *O*₂. When the motion of the diaphragm begins the current undergoes variations which are recorded by *O*₂. During the time of making an exposure the milliammeter is shunted so as to do away with all possible self induction in the transmitter circuit.

PHOTOGRAPHS AND MEASUREMENTS

Some reproductions of the photographs are shown in Figs. 6 and 7. The trace on the left shows the current in the magnet coil. The zero line is not shown but would traverse the middle of the trace as this is due to a simple alternating current. The straight dark line on the right gives the line for zero current in the transmitter. The trace to its left gives the variation of current through the transmitter when the diaphragm is oscillating. That is, the distance from the zero line to the trace at any point gives the instantaneous value of the current, and the difference between the maximum and minimum distance gives the range of oscillation of the current. The frequencies are given to the right.

On the plates for 600, 700, 940 and 1014 cycles, and on most of the plates not reproduced, the traces are pointed for maximum current (granules compressed) and flat for minimum current. In these cases the steady current line runs nearer the minimum than the maximum. This was shown by an asymmetrical broadening of the light spot toward the left when the exciting current was turned on, and also by a rise in the reading of the milliammeter *A*. In the first plate shown, namely for 288 cycles, this is reversed. The points are for minimum current and the flat side for maximum. In this case the steady current line runs nearer the maximum, the broadening being asymmetrical to the right, and correspondingly, the milliammeter fell on making the exciting current. The plate for 1350 cycles gives a more symmetrical trace of 288 $\sim$, but showed the same anomalous behavior in the broadening of the light spot toward less current, and the dropping of the milliammeter. These two plates were taken one after the other. This anomalous condition had been observed visually on one occasion when observing the oscillations by means

of a ground glass and a rocking mirror, but the transmitter had gone back to its normal condition before a photograph was obtained. After this no amount of tapping and exciting would bring it back. The plates in question were obtained when at the end of a series of exposures this condition was found to exist accidentally. After these two plates the transmitter returned to

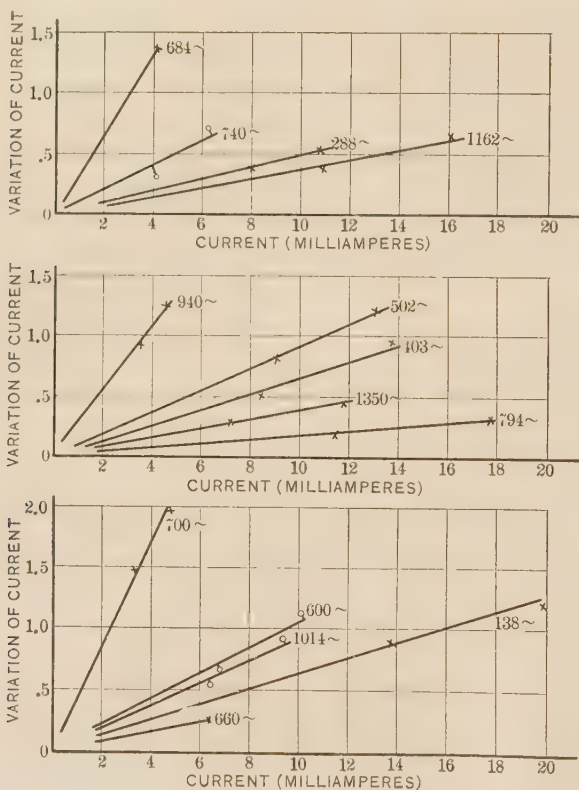


FIG. 15.—RELATION BETWEEN CURRENT THROUGH THE COIL OF THE MAGNET, AND THE VARIATION OF THE CURRENT THROUGH THE TRANSMITTER.

its normal state. Later one more anomalous trace was obtained at 660 but this does not fit in well with the others. The peculiarity did not seem to occur at any definite frequency, but seemed to depend entirely on the arrangement of the granules, for when once present it showed over a wide range of frequency, and when absent the same frequency could be gone over with normal results. It is not to be confused with ordinary "packing" but may be

closely allied to it. The traces for the transmitter in general show a great deal more distortion than do those for the receiver. The actual range of force on the diaphragm is considerably less for the transmitter, as the air gap between the magnet and disk is greater, and the amplitude of the current in the magnet is less.

Plotting for each frequency the current in the magnet as abscissa, and the variation of current in the transmitter, per milliampere of steady current as ordinate, we get the curves of Fig. 15. This relation between the two is seen to be approximately linear. The point farthest out usually shows a somewhat steeper slope, but in several cases the reverse is true. The accidental errors due to changes in the transmitter are, of course,

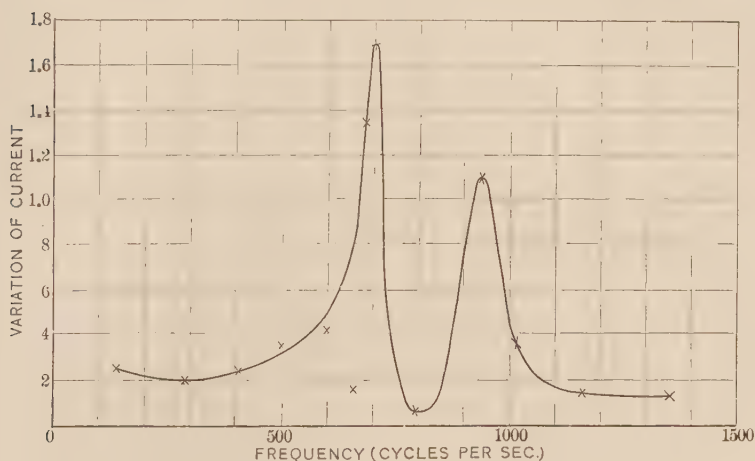


FIG. 16.—RESONANCE CURVE FOR THE TRANSMITTER.

great, so a straight line running between the two points was considered a fair locus for the curve. In Fig. 16 a curve is plotted having frequencies as abscissas, and as ordinates the variation of current in the transmitter per milliampere of steady current, when the current in the magnet has a constant value of four milliamperes. This is the resonance curve for the diaphragm. The points all fall fairly well into line except the one for 660 $\sim$, which is the one exposure made when the transmitter was for the second time in the anomalous state. The two plates obtained when it was for the first time in this state fall into line very well. The resonance curve certainly does not include the point at 660 $\sim$, as the light spots were watched vis-

ually, when the granules were in normal condition, and no drop in amplitude at that frequency was ever noticed. The light spots were watched time and again as the generator accelerated or came to rest; and it was easy to see the marked continuous rise and fall in the width of the oscillation. Whatever errors may have crept into the determination of one or two of the points the general nature of the resonance is certainly that of Fig. 16.

We notice in the curve the slight fall before the first maximum which was present in the receiver diaphragm curves, and is probably due to the losses in the magnet. Next the sharp maximum at 700, the minimum at 800, the second maximum at 940, and after this the drop to a fairly constant value. It is regretted that the investigation could not be pushed above 1350; but at higher frequencies conditions became very unsteady, especially is this true of the average current through the transmitter. It is a great surprise to find such sharp maxima in the curve, and two so close together. The ordinate of the first maximum is seen about eight and a half times that at the minimum, and six and a half times that at the lowest frequency; at the second maximum about eighteen times that at the minimum just before it, and about four times that at the lowest frequency. The location of the fundamental vibration at 700 cycles is in good agreement with Gati's work. It is to be regretted that no data can be obtained from his results regarding the sharpness of the resonance. His curves having as ordinates the current in a secondary circuit have a zero ordinate for zero frequency, *i.e.*, they start from the origin. Hence no comparison between the amplitude at resonance with that at zero frequency can be made.

The first resonance of the diaphragm we would naturally suppose to be due to its vibration as a whole. The second may be introduced by one of the so-called damping springs. The diaphragm in most modern transmitters, and in the one here worked with, is held in place by two pieces of spring steel about $\frac{3}{8}$ in. wide $1\frac{1}{2}$ in. long and 0.01 thick. These have rubber tips on the ends. One presses against the diaphragm at the edge; and the other one, some distance in towards the center. Now the point where the second one presses is more firmly supported than the points in its vicinity, so the second resonance may be due to a vibration of irregular configuration with this point lying on a nodal line. If this is the case one of the actions of the damping springs is just the opposite to that commonly supposed. Accord-

ing to Kempster B. Miller:¹⁰ "The object of these damping springs is to prevent too great an amplitude of vibration of the diaphragm, and also to keep it from vibrating in separate parts instead of as a unit." The inside damping spring may also have considerable influence in raising the fundamental period of the diaphragm as it adds to its stiffness. It should be possible to settle these questions by placing both springs on the edge and taking another resonance curve. It is hoped to do this in the near future.

SUMMARY OF RESULTS

Photographs have been obtained showing the vibration of receiver diaphragms when approximately harmonic currents are passed through the receiver. These show considerable distortion at some frequencies and very little at others. At any one frequency the distortion is less for smaller currents. This is what would be expected from *a priori* consideration.

An approximately linear relation has been shown to exist between current and amplitude of oscillation of the diaphragm over the range of work, which extends well beyond that of practice. Resonance curves for two receiver diaphragms have been plotted giving quantitative data of the influence of the natural period of the diaphragm.

The effect of a small load on the form and range of the oscillation was examined. Its influence could not be detected except in one instance in which there was possibly a slight effect on the range of oscillation.

Diametral vibrations of the diaphragm were observed in cases in which they would not have been expected from the apparent symmetry of the instrument. The orientation of the diaphragm over the pole pieces was observed to have a marked effect. It has not been experimentally settled whether this is due to the mirror or the grain of the plate, but it is difficult to see how a mirror weighing only 4 mg. could cause the vibrations. It is suggested that by properly introducing "diametral" vibrations the transmission of speech might be improved.

Photographs have been obtained showing the variation of current in the transmitter when an approximately harmonic force acts on the diaphragm. These show a rather marked distortion even for the lowest exciting force used, which was very much lower than the lowest force used on the receiver diaphragm.

10. American Telephone Practice. 4th edition, p. 56.

These distorted curves may be just reversed from their normal form when the microphone is in a certain abnormal state.

An approximately linear relation exists over the range examined between the variation in current and the exciting force. The resonance curve of the transmitter is given showing very marked maxima and minima. The first maximum is attributed to the fundamental period of the diaphragm vibrating as a whole. The second maximum is attributed to the diaphragm vibrating in an irregular configuration on account of the damping springs.

BIOGRAPHICAL NOTE.

Charles Ferdinand Meyer, son of Charles Meyer and Nanny Gail, was born in Baltimore on January 15, 1887. His early education was received at the Friends' School in Baltimore. In 1903 he entered the Johns Hopkins University, and in 1906 was admitted to the degree of Bachelor of Arts. From November, 1906 until September, 1907 he was in the employ of A. Schumacher & Co., General Agents for the North German Lloyd Steamship Co., in Baltimore. In October, 1907 he entered the Johns Hopkins University as a graduate student taking Physics and his principal subject, Physical Chemistry as first subordinate, and Mathematics as second subordinate. While at the University he attended courses given by Professors Ames, Wood, Whitehead, Bliss, Jones and Cohen, Drs. Pfund and Anderson, and Mr. Sparrow. During the year 1910-1911 he held a Fellowship in the department of Physics.

